PRELIMINARY REPORT ON

THE WATER RESOURCES OF THE WAILUKU AREA

MAUI

Circular C61

Prepared by the

UNITED STATES GEOLOGICAL SURVEY

in cooperation with

Division of Water and Land Development

DEPARTMENT OF LAND AND NATURAL RESOURCES

State of Hawaii

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By George Yamanaga and C. J. Huxel, Jr.

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DEPARTMENT OF LAND AND NATURAL RESOURCES
State of Hawaii

Honolulu, Hawaii
December 1970

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PRELIMINARY REPORT ON THE WATER RESOURCES OF THE WAILUKU AREA, MAUI

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SUMMARY

Water is normally plentiful in the Wailuku area and no serious shortage occurs, although at times local irrigators find the amount presently developed insufficient for optimum growth of sugarcane. This condition is partly caused by the exportation of a large part of the water available in the area to lands on the adjacent isthmus.

All perennial streams in the area except Makamakaole Stream derive their base flows from water draining from high-level, dike-held ground-water bodies lying within the West Maui Mountain. The largest sources of water are the Waihee River and Iao Stream. Waikapu and Waiehu Streams also supply significant amounts of water for irrigation.

Ground water occurs as high-level, dike-held water within the mountain mass, or as basal water and as perched water. The most promising source of additional water for use during drought periods appears to be a basal-water body in the area between Waikapu and Waihee Valleys.

INTRODUCTION

Purpose and Scope

The purpose of this report is to outline the occurrence of water in the Wailuku area and to summarize what is known of the quantity and quality of water available for development. The report describes briefly the geology, the streams, and the modes of occurrence of ground water. It summarizes available information on streamflow and ground-water occurrence, discharge, and quality, and outlines information needed for more comprehensive appraisals of the water supply.

It is the second of a series outlining the water situation on the island of Maui and completes the preliminary survey of West Maui. The first report covered the Lahaina District or the western part of West Maui (Yamanaga and Huxel 1969).

Extent and Character of Area

The area covered in this study, about 75 square miles in extent, is mainly the part of the Wailuku District which lies in West Maui. The eastern part of the Wailuku District is not included (fig. 1).

Drainage basins range in character from the dry gulches south of Waikapu to the deep valleys between Waikapu and Waihee (fig. 2). The long, narrow, gently sloping valley of Kahakuloa is similar to Honolua and Honokohau Valleys in the northern part of the Lahaina District.

Previous Investigations and Acknowledgments

Stearns and Macdonald (1942) include this area in their island-wide study of the geology and ground water of Maui.

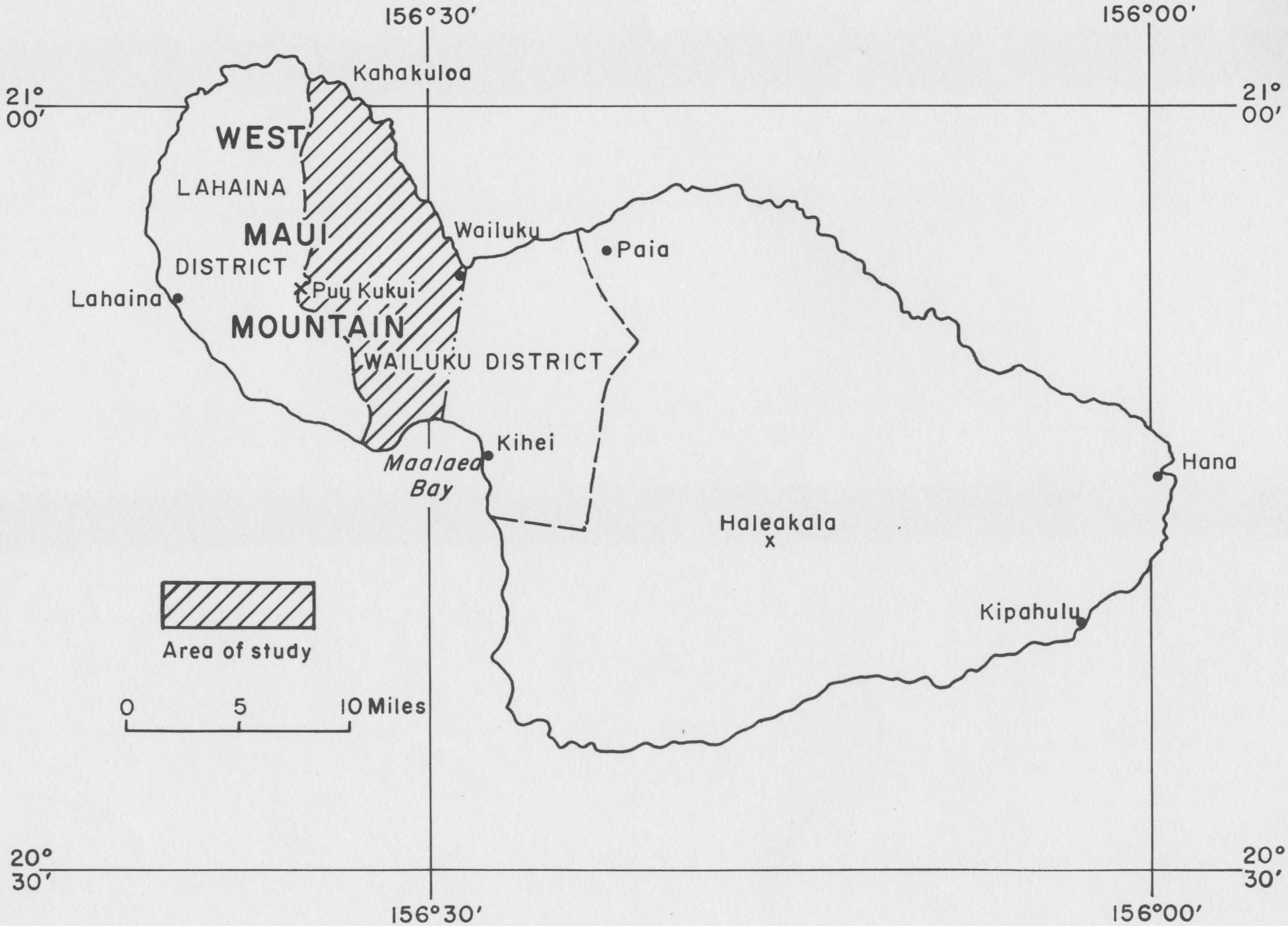

Figure 1. MAP OF MAUI SHOWING LOCATION OF THE WAILUKU AREA

Caskey (1968) has made a study of the basal-water body between Waikapu and Iao Valleys.

Surface-water information was systematically obtained for the first time in 1910, with the installation of a recording station on Iao Stream and staff gages on Waihee, Waiehu and Waikapu Streams, and on the main diversion ditches in the areas (Martin and Pierce, 1913). Records for these and other stations have been published in water supply papers of the U.S. Geological Survey.

Data compiled by the Wailuku Sugar Co. and Maui County Board of Water Supply were also utilized in preparing this report. The writers are particularly grateful for the cooperation of Dr. Doak C. Cox, Director, Water Resources Research Center, University of Hawaii, who provided access to correspondence and data in his personal files, as well as to the official files of the Center.

GEOLOGY

The geology of West Maui was described in detail by Stearns and Macdonald (1942, p. 156-187). The Wailuku area lies on the east side of the deeply dissected dome of volcanic rocks called West Maui Mountain. West Maui Mountain is nearly circular in plan and is asymmetric in profile. The volcanic flows on the east and south sides dip more steeply than those on the north and west sides. The dome has been reduced by erosion from a summit altitude estimated to have been 7,000 feet (Stearns, 1942, p. 156) to 5,788 feet at Puu Kukui.

Exposed volcanic rocks of West Maui Mountain are lava flows, dikes, and pyroclastic deposits ranging from Pliocene(?) to late Pleistocene or Holocene in age (Stearns, 1966, p. 157). On the basis of lithology and stratigraphic position, these rocks are differentiated into the Wailuku, Honolua, and Lahaina Volcanic Series. The occurrence of the Lahaina Volcanic Series in the Wailuku area is limited to a small cinder cone near Maalaea. Sedimentary rocks consist of consolidated older alluvium and dune sand of Pleistocene age, and unconsolidated younger alluvium and beach deposits of Holocene age.

The areal distribution of rocks in the Wailuku area is shown in figure 2, and their lithology and water-bearing characteristics are summarized in table 1.

Volcanic Rocks

Wailuku and Honolua Volcanic Series. The great bulk of the rocks making up West Maui Mountain, and constituting the principal aquifer, is olivine basalt of the Wailuku Volcanic Series. The lava flows of the Wailuku Volcanic Series are mostly thin bedded and scoriaceous and are characterized by

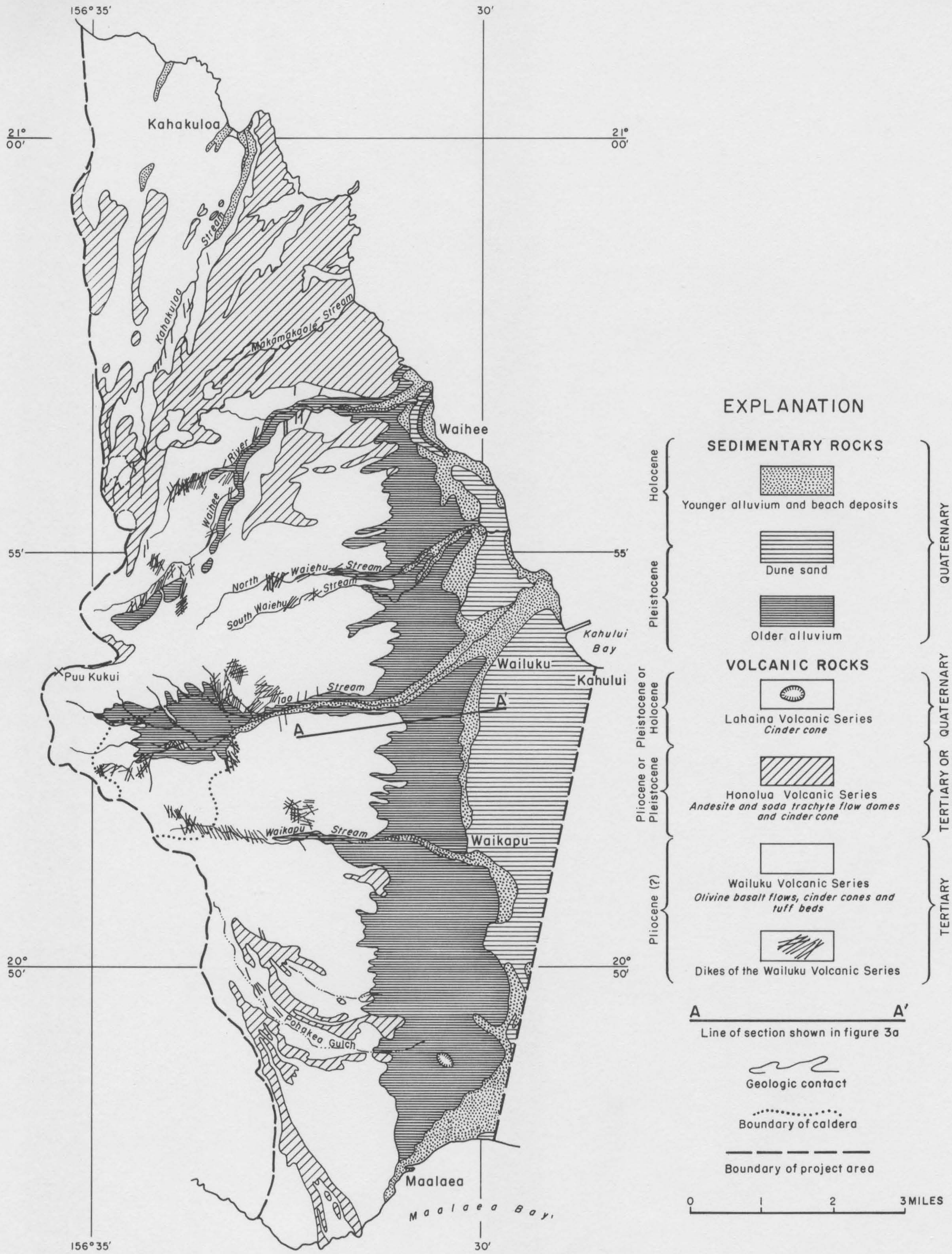

Figure 2. GENERALIZED GEOLOGIC MAP OF THE WAILUKU AREA

Table 1. GEOLOGIC UNITS AND THEIR WATER-BEARING CHARACTERISTICS

Geologic type	Age	Maximum thick-ness (feet)	Geologic unit	Lithology	Water-bearing characteristics
Sedimentary deposits	Holocene	75±	Younger alluvium	Unconsolidated silt, sand and gravel in the lower reaches of major valleys and surrounding the base of the older alluvial slope. Interbedded with beach sand and gravel underlying the coastal plain.	Permeable deposits of stream sand and gravel yield around 600,000 gpd (gallons per day) to tunnels 8, 9, and 10 in Iao and Waihee Valleys; deposits of silt, sand, and gravel surrounding the coalescing fans of the older alluvial slope contain perched water but are generally impermeable; beach deposits near the coast yield brackish water which may be under basal conditions locally.
	Pleistocene and Holocene	200±	Dune sand	Consolidated, fine-grained crossbedded sand formed into prominent dunes on the coastal plain and on the isthmus east of the older alluvial slope.	Permeable but not known to be an aquifer because of its elevation above the surrounding plain. Springs occurring along the seaward side at the base of the dunes between Wailuku and Waihee point probably emanate from the contact between the dune sand and the underlying older alluvium. Where they extend below sea level on the coast they may carry brackish water.
		700+	Older alluvium	Alluvial conglomerate consisting of consolidated, unsorted beds of boulders, gravel, sand silt, and clay and comprising coalescing alluvial fans which form the extensive alluvial slope stretching from Maalaea to Waihee. Underlies most of the major stream channels.	Impermeable and unimportant as a source of water supply Extends several hundred feet below sea level in places and forms a caprock barrier to the eastward flow of basal water from Maalaea to Waihee.
Volcanic rocks	Holocene or Pleistocene	--	Lahaina Volcanic Series	Cinder cone on alluvial slope near Maalaea.	Insignificant in areal extent.
	Pleistocene and/or Pliocene	1,000±	Honolua Volcanic Series	Massive lava flows and domes of andesite and soda trachyte. Flows separated by interflow clinker zones; scattered cinder cones; few exposed dikes.	Permeable only along interflow clinker zones, Springs emanating from a clinker bed supply the base flow of Makamakaole Stream. Low permeability probably inhibits recharge to basal-water body in the Wailuku basalts between Waihee and Kahakuloa Valleys.
	Pliocene(?)	5,500±	Wailuku Volcanic Series	Thin-bedded aa and pahoehoe flows of primitive olivine basalt; scattered cinder cones and thin tuff beds; caldera deposits in upper Iao Valley; numerous dikes.	The basalt flows are highly permeable and constitute the main aquifer of West Maui. Dikes are dense and impermeable and retard or divert ground-water flow in the basalt flows through which they cut. Basal water is developed by wells and a shaft. The three Mokuhau wells pump between 3 and 5 mgd (million gallons per day) and three wells in the Wailuku shaft (No. 33) have a bombined capacity of 15 mgd.

structural features such as interflow clinker beds, scoriaceous zones, lava tubes, and joints. These features render them highly permeable. Where they have never been covered by younger volcanic rocks, they are weathered as deep as 100 feet. Individual flows range in thickness from 1 to 100 feet.

North of Waiehu Valley and south of Waikapu Valley, the Wailuku basalt flows are overlain in places by andesite and soda trachyte of the Honolua lava flows which are denser and more massive than the underlying Wailuku basalt. They range in thickness from about 50 to 750 feet and are generally more resistant to erosion than the weaker basalt. Stearns (1942, p. 174) found that the Honolua lava flows were originally more extensive than at present and probably reached their greatest thickness on the northern flank of West Maui Mountain.

Pyroclastic deposits of the Wailuku and Honolua Volcanic Series are not extensive and are generally unimportant hydrologically. Vitric tuff beds of the Wailuku Volcanic Series act as perching members supporting small bodies of ground water in the northern part of the area (Stearns, 1942, p. 63).

The limits of the caldera complex of the Wailuku Volcanic Series are outlined in figure 2. The materials making up the caldera complex are relatively low in permeability (Stearns, 1942, p. 166).

Dikes. The basalt flows of the Wailuku Volcanic Series are cut by numerous dikes, many of which are exposed in the walls of the major valleys. The dikes range in thickness from a few inches to as much as 35 feet. Major dike systems extending northward and south-southeastward from Iao Valley were recognized by Stearns (1942, p. 163), and general north-south rift zones paralleling the dike systems were mapped by him (1942, p. 81). More recent work (Malahoff and Woollard, 1966, p. 275, 296) shows evidence of a major east-west rift zone.

The vertical dikes which intrude the Wailuku flows form fairly impermeable barriers, causing ground water to move generally parallel to the major dike trends. Where dikes intersect, they form compartments within which ground water is impounded. Distribution and orientation of dikes are shown in figure 2.

Sedimentary Deposits

Older Alluvium, Dune Sand, Younger Alluvium, and Beach Deposits. A period of extensive erosion followed the eruption of lavas of the Honolua Volcanic Series and the major West Maui valleys were cut to depths of several hundred feet below present sea level. A later rise in sea level caused the deposition of thick accumulations of older alluvium in the valleys, and a sloping alluvial plain consisting of coalescing alluvial fans was formed stretching from Waihee to Maalaea.

The older alluvium is a poorly sorted, partly to completely consolidated conglomerate, consisting of particles ranging from large boulders to clay. It is poorly permeable and inhibits the flow of basal water seaward and eastward from the basalts of the Wailuku Volcanic Series.

The older alluvium is thickest along the axes of the major valleys. In the lower reaches of Iao Valley, where test hole T-113 (fig. 7) penetrated more than 700 feet of alluvium and interbedded lava, the older alluvium extends to at least 524 feet below sea level.

Deposits of consolidated calcareous dune sand thinly veneer the older alluvium on the isthmus east and south of Wailuku and along the coast between Wailuku and Waihee Point. The dunes have a significant amount of relief and are prominent features on the otherwise flat to gently sloping isthmus and coastal plain. The dune-sand deposits are permeable, and Stearns (1942, p. 131) observed basal springs flowing from their seaward edge between Iao and Waiehu Valleys.

Younger alluvium consisting of silt, sand, and gravel has been deposited in the present-day stream channels cut into the older alluvial fans and at the bases of the fans. In the stream channels, the younger alluvium is fairly permeable and contains appreciable amounts of fresh ground water. The younger alluvium deposited at the base of the older alluvial slope is, however, poorly permeable. Near the shore, the younger alluvium is interbedded with marine sand and silt. The deposits along the coast are locally permeable and contain brackish water.

The stratigraphic relations between some of the major geologic units are shown in figure 2a.

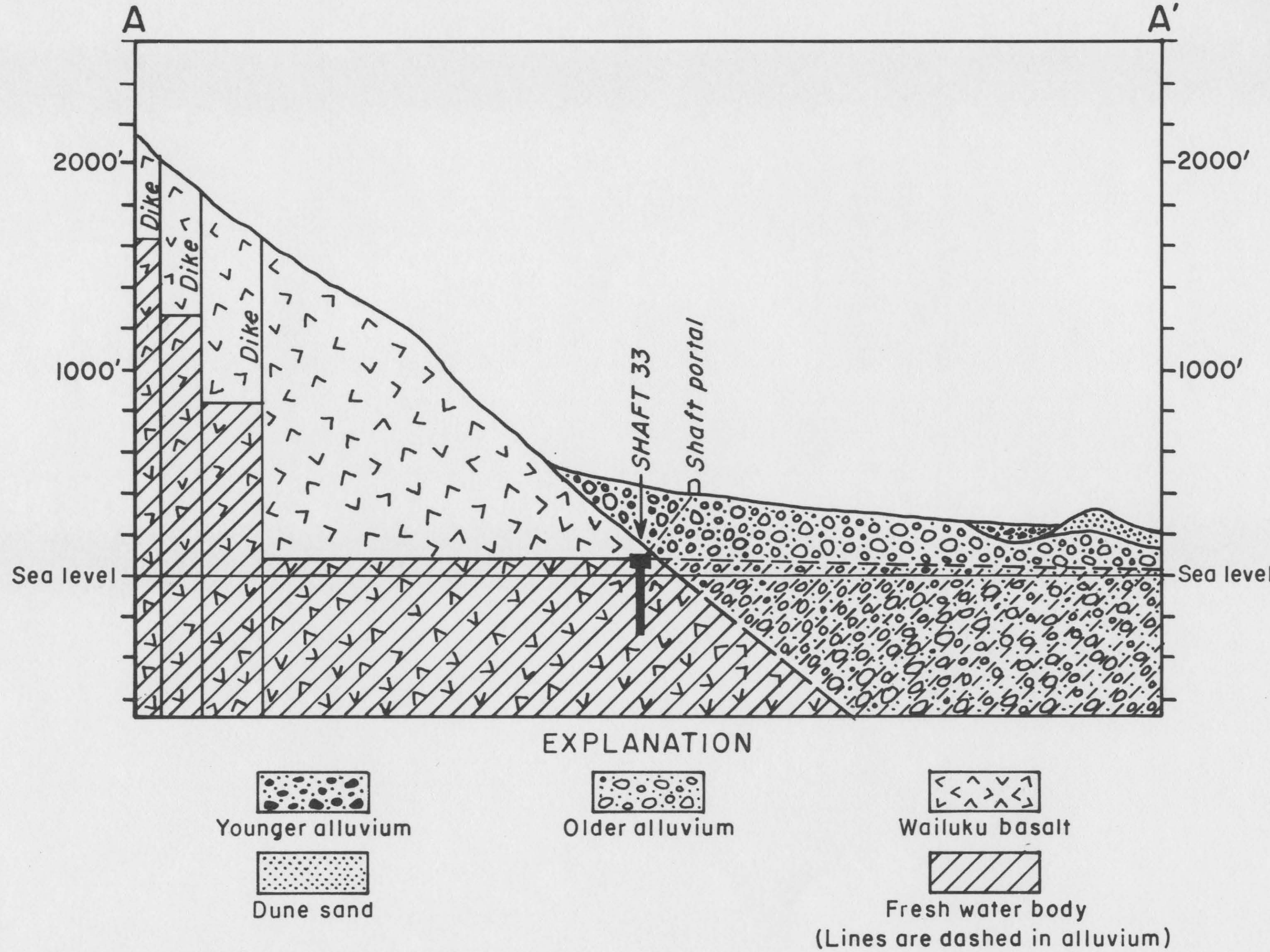

Figure 2a. GENERALIZED GEOLOGIC SECTION THROUGH DIKE WATER AND BASAL-WATER RESERVOIRS (Location of section shown on figures 3 and 7)

RAINFALL

Records indicate that rainfall in this area ranges from less than 15 inches per year near Maalaea to about 400 inches per year at Puu Kukui (fig. 3). The total amount of rain for the area can only be estimated only roughly, however, because although there are many rain gages in the cultivated lowlands, very few have been placed in the remote, rugged, mountainous uplands. The only points above 1,300-foot altitude where rainfall records have been collected are Iao Valley (380.1) at 1,720 feet from 1911 to 1914, Eke (481.3) at 4,600 feet from 1913 to 1933, and Kukui (380) at 5,788 feet from 1925 to the present. For a large part of the area, especially where rainfall is high, no accurate measurements are available.

The rainfall map presented in figure 3 is a composite of meteorologic data through 1955 and was prepared by the U.S. Weather Bureau, Honolulu[1/]. On the basis of this map, the total rainfall for the area is estimated to be about 370 mgd, of which about 210 mgd falls on watersheds above streamflow measuring points (table 2). The total rainfall on the areas tributary to the important basal aquifer between Waihee and Maalaea is about 230 mgd (table 3). The watershed areas for which rainfall is estimated are shown in figure 3.

Variation of rainfall is illustrated in figure 4, on which annual rainfall at several rain gages are plotted. Rain gage 307 (reservoir 9) and its replacement, 307.2 (Pohakea Bridge) are in the drier southern end of the study area. The effects of location and exposure are illustrated by the graphs for

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[1] Saul Price, 1969, U.S. Weather Bureau, personal oral communication.

Table 2. ANNUAL RAINFALL AND RUNOFF DATA FOR SELECTED WATERSHED AREAS

Watershed	Altitude of measuring site (ft above msl)	Area of Watershed above measuring site (sq mi)	Rainfall on area (mgd)	Runoff from area (mgd)	Amount diverted and used (mgd)
Waikapu	880	2.2	19	10	3
Iao	860	5.4	77	50	18+[a]
South Waiehu	870	.87	6	5	3
North Waiehu	880	.85	7	5	3
Waihee	620	4.2	54	50	40
Makamakaole	1,500	.42	4	2	(b)
Kahakuloa	330	3.3	37	11	(c)
Total (rounded)		17.2	214	133	

a Some additional water diverted during high flows not included.
b Small amount diverted for stock use.
c Undetermined amount diverted for taro irrigation.

Table 3. RAINFALL IN DRAINAGE BASINS TRIBUTARY TO THE BASAL AQUIFER BETWEEN WAIHEE AND MAALAEA*

Watershed	Gaged part of watershed Area (sq mi)	Gaged part of watershed Annual Rainfall on area (mgd)	Ungaged part of watershed Area (sq mi)	Ungaged part of watershed Annual Rainfall on area (mgd)	Total watershed Area (sq mi)	Total watershed Annual Rainfall on area (mgd)
Maalaea	--	--	9.37	19	9.37	19
Waikapu	2.22	19	1.83	7	4.05	26
Iao	5.43	77	3.90	16	9.33	93
Waihee-Waiehu**	5.96	67	5.41	28	11.37	95
Total (rounded)	13.6	160	20.5	70	34.1	230

*The seaward boundaries for the watersheds coincide with the contact between the flows of the Wailuku Volcanic Series and the older alluvium.

**Combined area consisting of the Waihee, South Waiehu, and North Waiehu watersheds.

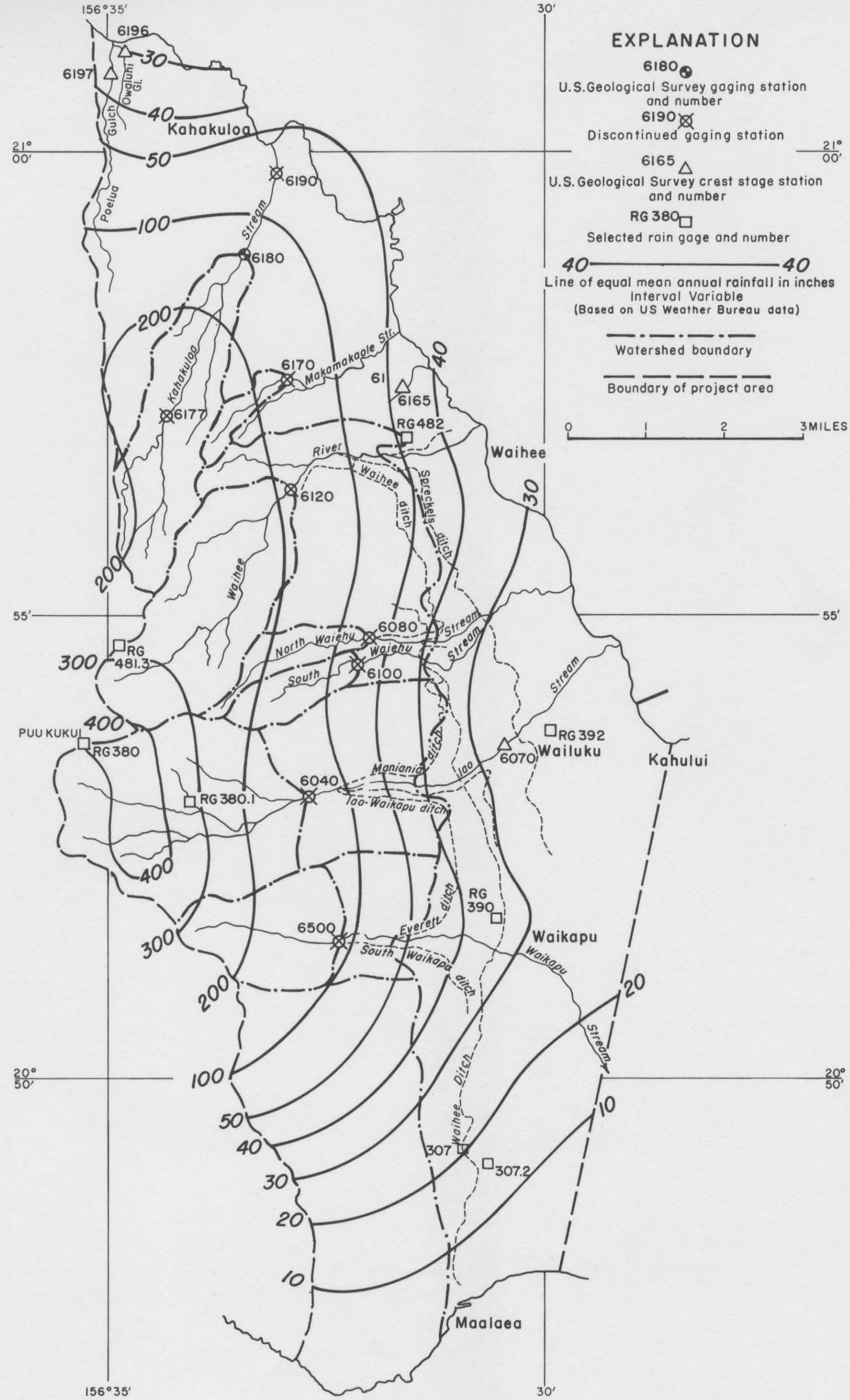

Figure 3. MAP OF AREA SHOWING DISTRIBUTION OF MEAN ANNUAL RAINFALL AND LOCATION OF SELECTED RAINFALL AND STREAMFLOW STATIONS, AND MAJOR DITCHES

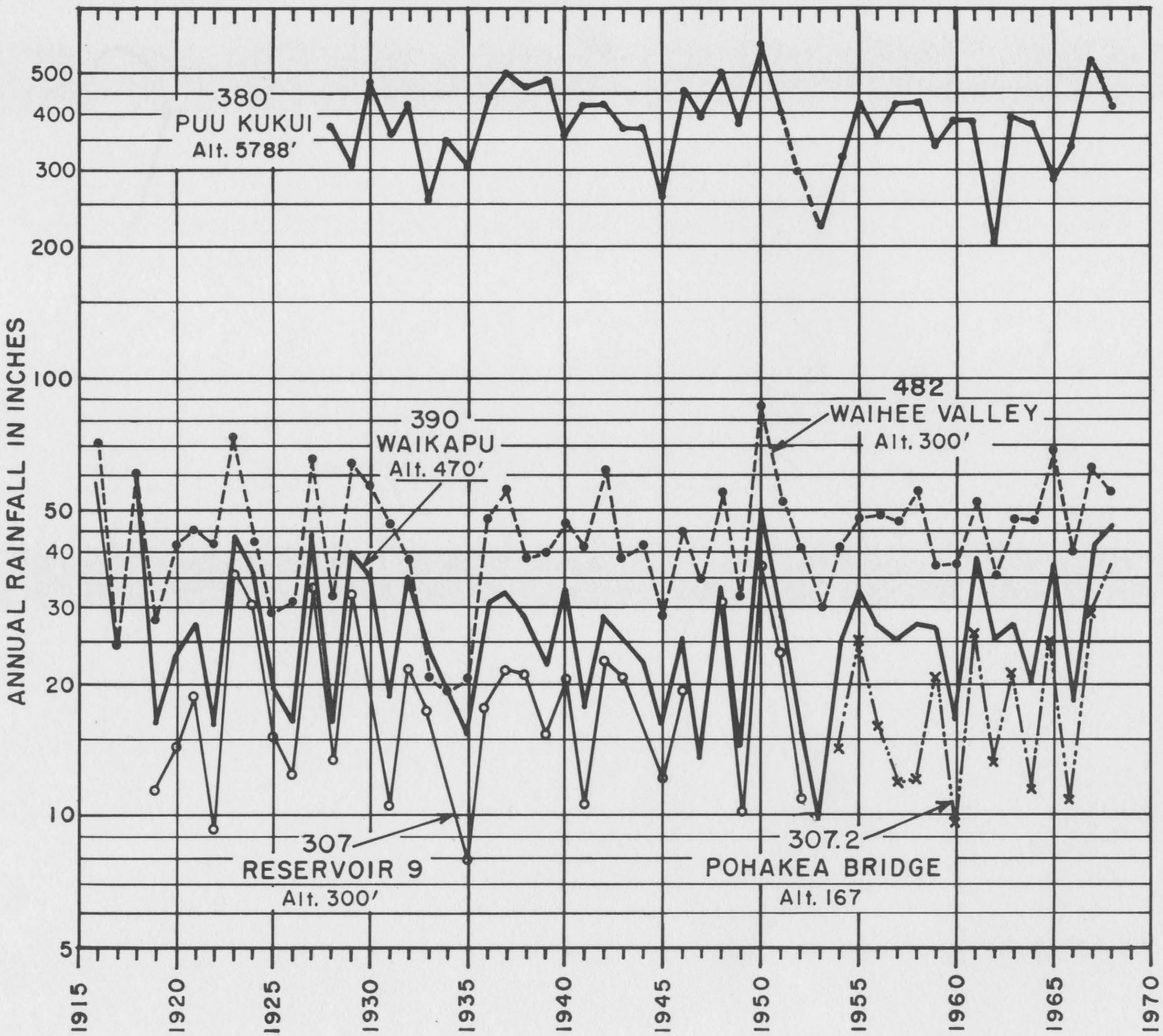

Figure 4. GRAPHS SHOWING VARIATION OF ANNUAL RAINFALL AT SELECTED SITES

gage 482 (Waihee Valley) and gage 390 (Waikapu). Though rainfall in Hawaii generally increases as altitude increases, rainfall at 482, at altitude 300 feet, which is located farther north and away from much of the tradewind blocking effects of the Haleakala volcanic dome, is nearly twice that at 390, at altitude 470 feet; the average annual rainfall for 1931-60 is 42.45 inches at 482 and 24.71 inches at 390.

Monthly variations in rainfall are illustrated in figure 5. Rainfall during May to September is less than 20 percent of that during December to April at 390, Waikapu, and about 35 percent at 482, Waihee Valley.

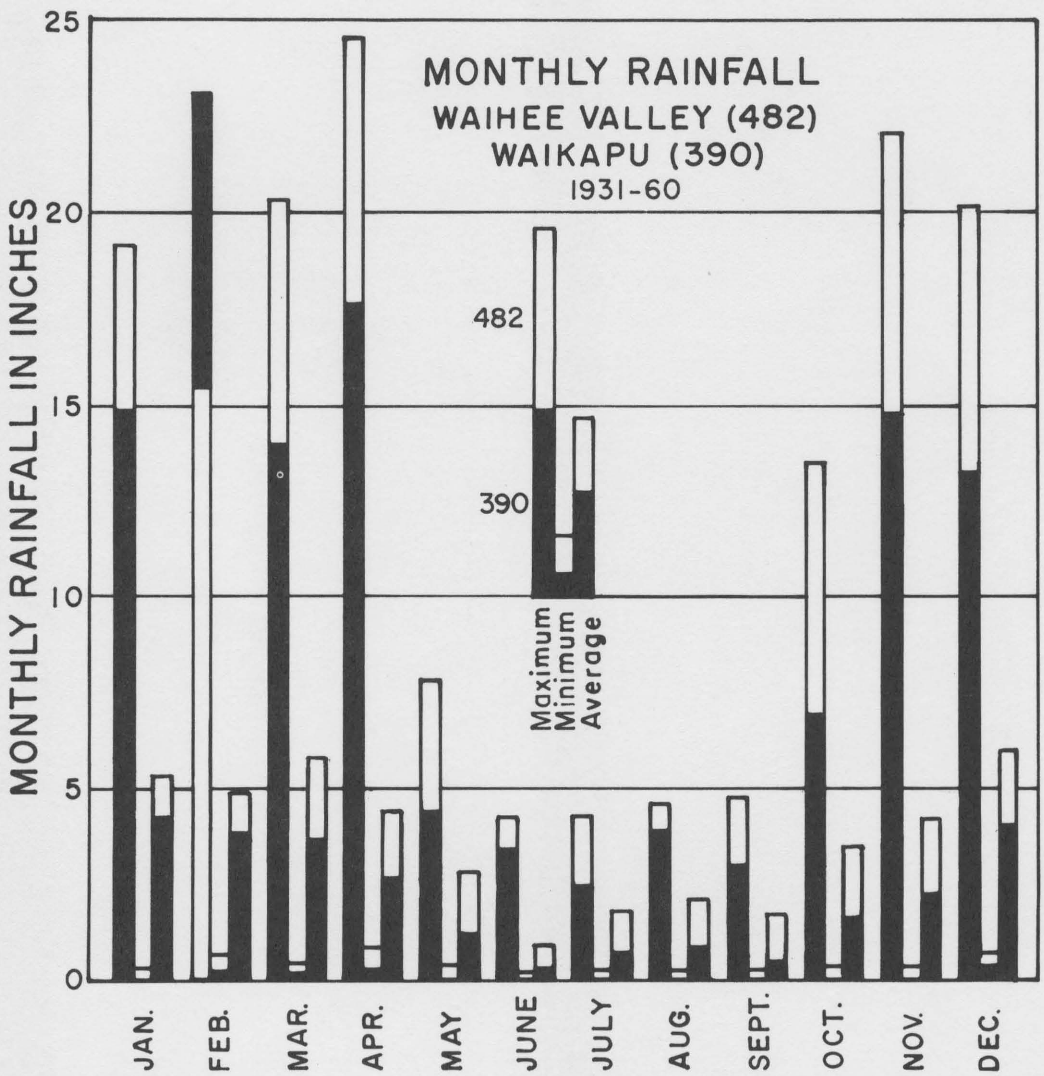

Figure 5. GRAPHS SHOWING MAXIMUM, MINIMUM, AND AVERAGE MONTHLY RAINFALL AT WAIKAPU (390) AND WAIHEE VALLEY (482)

WATER RESOURCES

Streamflow

Two of the largest streams on Maui are in the central part of the Wailuku area. Iao Stream and Waihee River, both fed by high-level, dike-held water bodies, supply more than half the water requirements of the area. Somewhat smaller Waikapu and Waiehu Streams also supply some water for sugarcane irrigation. Other perennial streams, in the northern end of the area, are Kahakuloa and Makamakaole Streams, from which some water is diverted for taro cultivation and for stock use.

There are no perennial streams south of Waikapu Stream.

Records Available. Streamflow records in this area are few and fragmentary and the quantity of surface water available can only be estimated. The longest records are those for the U.S. Geological Survey gaging station on Kahakuloa Stream (6180). This station was operated from 1939 to 1943 and reestablished in 1947 and is the only full-range recording station now in operation in the study area. Gaging stations were operated for short-term periods on many streams in the area during the second decade of the century. Records from the short-term gaging stations (U.S. Geological Survey, 1961) form the main basis for estimates of streamflow given in this report. Other Survey gaging stations presently operated in the area are partial-record flood-flow stations: Iao Stream near Wailuku (6070), Owaluhi Gulch near Kahakuloa (6196), Poelua Gulch near Kahakuloa (6197), and an unnamed gulch between Makamakaole and Waihee Streams (6165). Data obtained from these stations are summarized in published reports (U.S. Geological Survey, 1961-67).

Wailuku Sugar Co. operates gaging stations on their main supply ditches--Waihee, Spreckels, North Waiehu, Maniania, Iao-Waikapu, Everett and South Waikapu ditches. Because of operational procedures, however, records from these stations are not truly indicative of natural flow in the streams from which water is diverted. These records are useful to the plantation for determining the amount of surface water used for irrigation of sugarcane. However, for this study they were used mainly to estimate the minimum flows of the streams from which water is diverted; the ditches usually take all available streamflow during low-flow periods.

Perennial Streams

Waikapu Stream. Waikapu Stream derives its base flow from breached high-level, dike-held water bodies near the head of Waikapu Valley, the southernmost of several large, deep valleys in the area.

Of the average discharge of 10 mgd (estimated on the basis of records obtained during 1911-17), about 3 mgd is used for sugarcane irrigation. The 3 mgd figure represents all the dry-weather flow of the stream and, consequently, the stream is usually dry at the highway crossing downstream of the diversion point. Partly as a result of this condition, the channel is not well developed in the lower reaches of the stream--below the highway crossing--and floodwaters have, at times, caused considerable damage to bordering canefields in this area.

Iao Stream. Iao Stream drains a large amphitheater-headed valley and is one of the principal sources of water in the area. It derives its base flow from ground-water leakage of breached dike compartments. The head of the valley has moved westward beyond the original divide between the east and west sides of the West Maui Mountain and some water that formerly flowed toward the ocean on the Lahaina side now flows into Iao Stream.

The valley has also increased its width and has captured some water that would have drained into Waikapu and South Waiehu Streams.

Records obtained during 1910-15 at gaging station 6040 indicate an average discharge of about 50 mgd. Wailuku Sugar Co. presently diverts an average of about 18 mgd (the entire flow during dry weather) through the Maniania and Iao-Waikapu ditches. During high-water periods, water, in excess of the capacity of the ditches, flows downstream where some of it is diverted by Hawaiian Commercial and Sugar Co.

Floods have caused considerable damage to areas along the lower reaches of the stream in spite of improvements made to the stream channel. The large quantities of boulders transported during high flows create a special problem in flood control.

Waiehu Stream. Waiehu Stream is formed by the confluence of South Waiehu and North Waiehu Streams, which are perennial because of leakage from dike compartments. These streams do not extend to the summit of the West Maui Mountain, being cut off by the more rapidly developed valleys of Iao to the south and Waihee to the north.

Records obtained from 1910 to 1917 indicate average flows of about 7 mgd for South Waiehu Stream (6100) and about 5.5 mgd for North Waiehu Stream (6080). However, the records are fragmentary and from staff-gage readings only, and the average flow for each of these streams is estimated in this report as nearly 5 mgd.

About 3 mgd is diverted from each of these streams for irrigation of sugarcane--by Hawaiian Commercial and Sugar Co. from South Waiehu and by Wailuku Sugar Co. from North Waiehu. Taro cultivation is still carried on below the diversions, and old water rights apparently remain in effect. As a consequence, Waiehu Stream tends to be perennial to its mouth.

Waihee River. Waihee River flows in a long, deep, narrow valley that drains the northeast slopes of the West Maui Mountain where rainfall is plentiful. The headward part of the valley has developed to such a point that it has cut off the headwaters of Waiehu Stream to the south and Makamakaole and Kahakuloa Streams to the north and is apparently in the process of capturing the headwaters of Honokohau Stream to the west.

Consequently, the flow of Waihee River is large. Records obtained during 1913-17 indicate that the average discharge at station 6120 is about 50 mgd. Rainfall on the basin is estimated to be 54 mgd.

Waihee River is the principal source of water in the area. Wailuku Sugar Co. derives about 22 mgd of irrigation water and Hawaiian Commercial and Sugar Co. about 18 mgd from the stream by diversion through Waihee and Spreckels ditches, which the companies operate on a cooperative basis. By agreement, Hawaiian Commercial and Sugar Co. has rights to all the water flowing in the river that can be taken into Waihee ditch between 6 p.m. and 4 a.m. and all remaining water that can be taken into Spreckels ditch between 5 p.m. and 5 a.m. daily. Outside of these periods, Wailuku Sugar Co. has rights to all waters of Waihee River. However, there exists prior rights for irrigation of taro lands downstream, and water for the taro lands is supplied, at times, by regulated release from Spreckels ditch.

Makamakaole Stream. Makamakaole is a small perennial stream that begins as flow from springs, which issue from clinker beds probably perched on weathered clinker and dense trachyte (Stearns, 1942).

A gaging station (6170) was operated on the left branch of the stream during 1939-52. Records indicate an average discharge of about 1.9 mgd. Measurements made in 1939 and in 1960 show that the flow in the right branch is only about 10 percent of that in the left branch.

A ditch diverts about 0.6 mgd from the left branch for stock use, and a 2-inch pipeline takes water from the right branch for use at a Boy Scout camp located nearby.

Kahakuloa Stream. Kahakuloa Stream flows with a gentle gradient in a long, narrow valley.

Kahakuloa Stream is the only one in this area that has been gaged for more than 15 years. Gaging stations have been established at three different sites on the stream; at altitude 1,380 feet (6177) between 1913 and 1915; at altitude 40 feet (6190) in 1913; and at altitude 390 feet (6180) from 1939 to 1943 and from 1947 to the present. An analysis of the records for the present site (6180) shows that the average discharge is about 11 mgd. Maximum, instantaneous discharge was 1,990 mgd on December 14, 1942. Minimum discharge, slightly less than 2 mgd, occurred in February, 1954. Reliable flow--flow exceeded 90 percent of the time--is 3.3 mgd (see figure 6).

An undetermined amount of water is diverted for irrigation of taro lands within the valley.

Ground-Water Occurrence

Ground water in the Wailuku area occurs as dike water, as basal water, and as perched water.

Dike Water. Dike water is impounded above sea level in compartments of lava bounded by intersecting dikes. Because of a radial dike pattern characterizing West Maui Mountain, the dike water occurs in an oval-shaped area underlying the central part of the mountain (fig. 7). The inferred eastern boundary between the dike-water and the basal ground-water areas is drawn (fig. 7) along the seaward edge of the dikes as mapped by Stearns, but buried dikes and dike water may actually extend considerably farther seaward.

Rainfall in the uplands of West Maui recharges the dike-water reservoir. Dike water discharges from springs and seeps

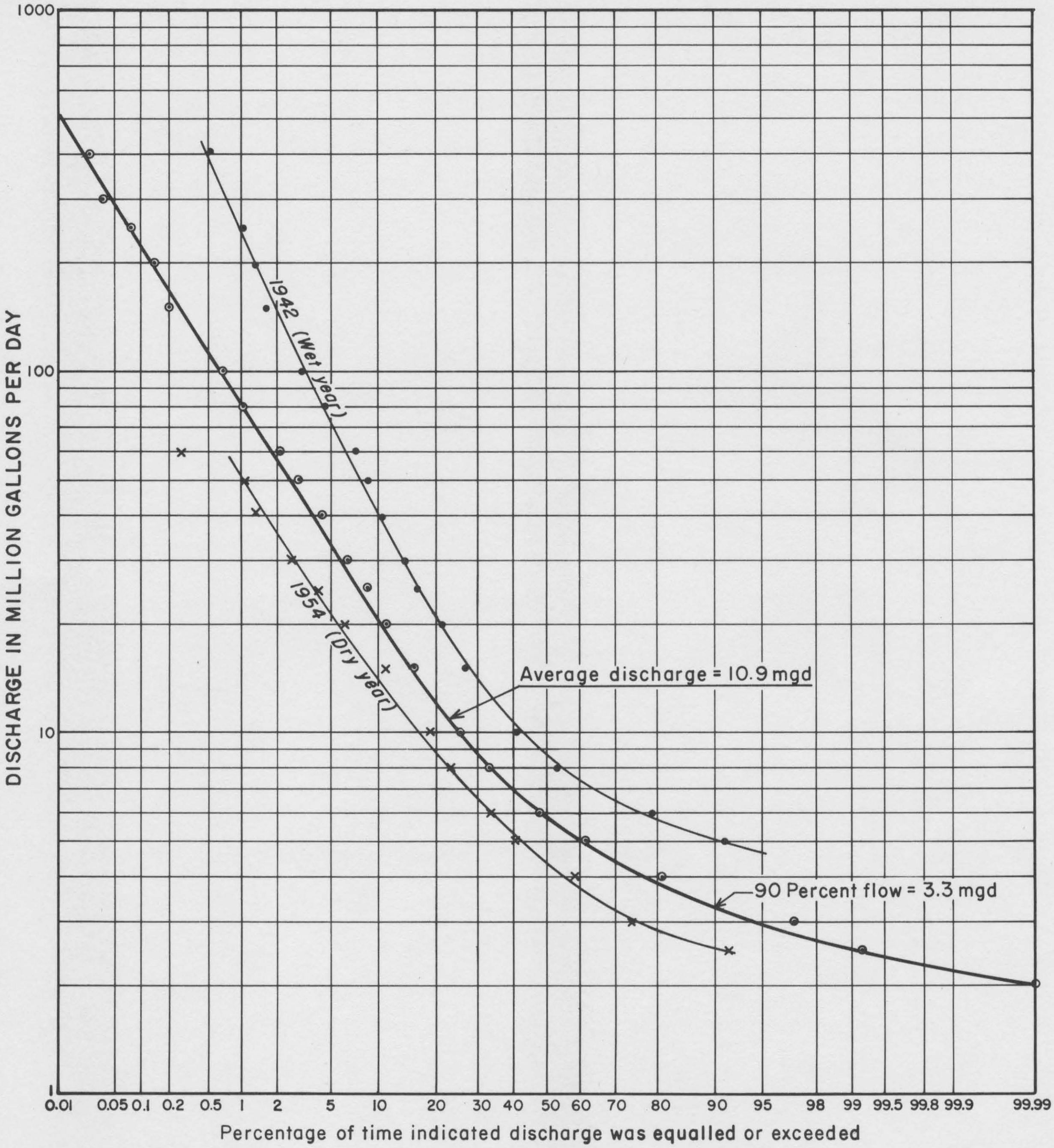

Figure 6. FLOW-DURATION CURVES FOR KAHAKULOA STREAM

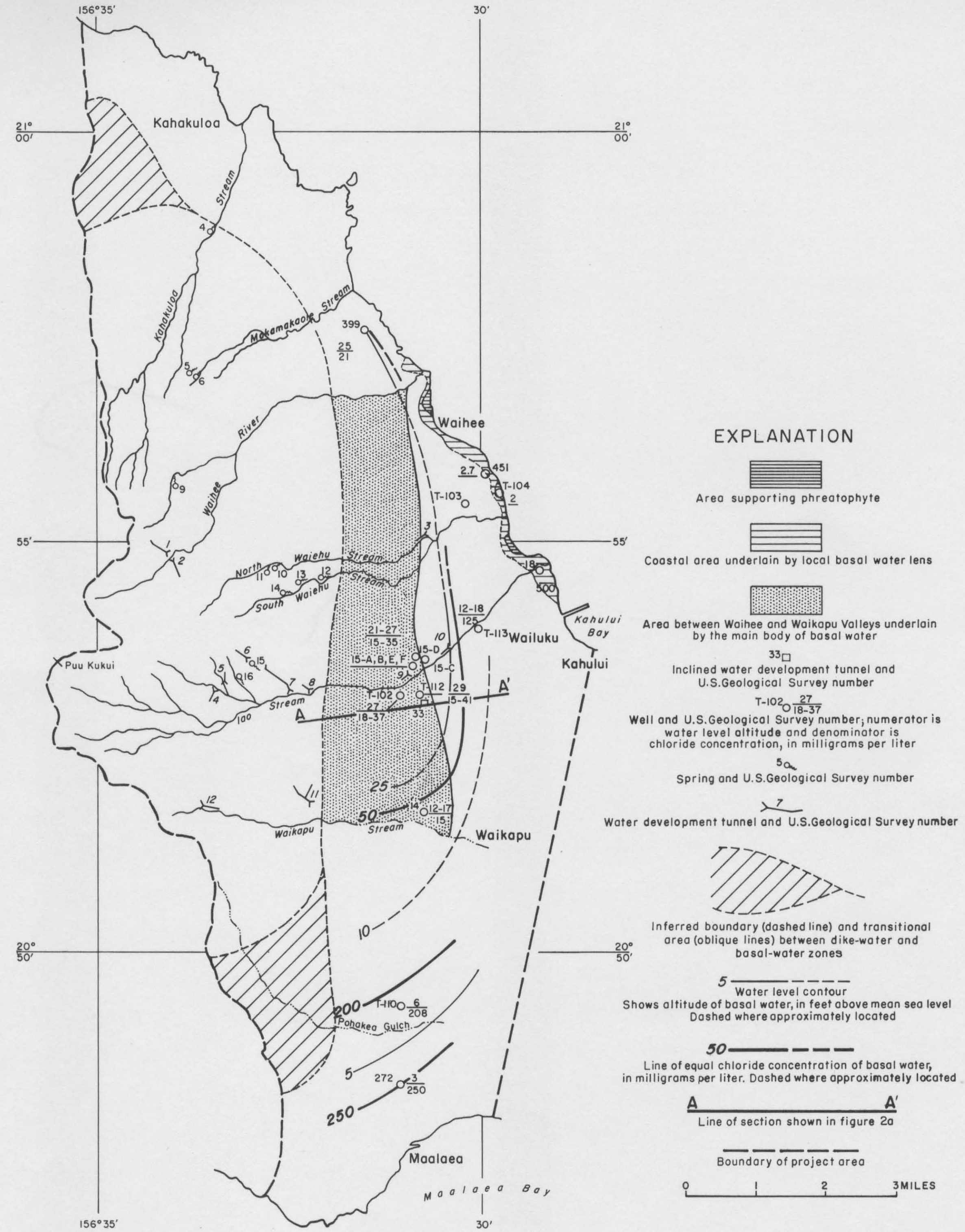

Figure 7. MAP SHOWING LOCATIONS OF SPRINGS, TUNNELS, WELLS, AND SHAFTS, PHREATOPHYTE AREAS, AREAS UNDERLAIN BY LOCAL BASAL-WATER LENS AND SEMICONFINED BASAL WATER, AND CHLORIDE CONCENTRATION

emanating from dikes breached by stream valleys, from development tunnels, and by ground-water underflow through and over the dikes. The average visible discharge of dike water in the gaged drainage basins of the Wailuku area was estimated by Stearns (1942, p. 46) to be about 47 mgd. The invisible discharge, or underflow, of the dike water to the basal-water body is not known.

Basal Water. Basal water is fresh water floating on sea water and lying seaward of the dike water. The basalt of the Wailuku Volcanic Series forms the reservoir for the main body of basal water; however, a thin local lens of basal water occupies the younger alluvium and dune-sand deposits along the coast between Wailuku and Waihee (fig. 7).

The boundary between the basal water and the high-level dike water may be sharp in places where the dikes intersect to form compartments. However, there may be a transitional relationship between dike water and basal water where the dikes are parallel. South of Waikapu Valley and west of Kahakuloa Valley, ground-water flow is parallel to the dike trends and the relationship is probably transitional because of the parallel orientation of dikes (figs. 2 and 7).

The top of the main body of basal water, as recorded in wells, ranges from less than 3 feet to about 30 feet in altitude. The thickest part of the basal-water body, and the most important from the standpoint of water-supply development, lies between Waikapu and Waihee Valleys (fig. 7). Water in the main basal-water body is impounded by the thick wedge of older alluvium extending from Waihee Valley to Maalaea (fig. 2a).

Recharge to the main basal-water body is primarily by underflow from the high-level water body and, to a much lesser extent, by deep percolation of rainfall and irrigation water through the overlying older alluvium. Discharge is by underflow beneath or around the older alluvial barrier, and by pumpage.

The nature of the basal water between Kahakuloa and Waihee Valleys is not known. However, well 399 encountered fresh ground water approximately 25 feet above sea level. This may indicate that the ground-water body here also is inhibited from flowing seaward by some impounding mechanism, and the area of impounded basal water may extend farther northward than is shown on figure 7.

The general configuration of the basal-water surface and the chloride concentration of the basal water in the area extending from Maalaea to Waihee Valley are shown in figure 7.

Perched Water. Ground water occurs perched in the younger alluvial sand and gravel of Iao and Waihee Valleys and in the consolidated dune sand between Waihee and Wailuku.

The younger alluvial sand and gravel deposits in Iao and Waiehu Streams and Waihee River channels are recharged by rainfall and by streamflow seepage. Discharge is by underflow downstream or through development tunnels.

Although the deposits of consolidated dune sand are permeable, they are generally thin, and, in most places, are elevated above the water table in surrounding deposits. They contain ground water perched on the underlying and less permeable older alluvium, and are recharged by direct infiltration from rainfall and by seepage from irrigated fields inland. Discharge is from springs and wells along the seaward base of the dunes.

Ground-Water Development

Development of high-level ground water consists mainly of diverting discharge from tunnels and major springs (table 4). Major springs from breached dikes in the Wailuku basalts

Table 4. TUNNEL AND MAJOR SPRING DISCHARGE, BASE FLOW, AND MEAN FLOW IN WAILUKU AREA VALLEYS

Valley or basin	Tunnel No.	Spring No.	Discharge[1/] (mgd)	Base flow[2/] (mgd)	Mean flow[3/] (mgd)
Kahakuloa		4	2.23	3.5[a]	11
Makamakaole		5	0.075		
		6	0.035		
Subtotal			0.11 [b]		2
Waihee	1		4.60		
	2		1.00		
		8	0.10		
		9	1.25		
Subtotal			6.95	25.0	50
Waiehu		10	0.15		
		11	1.50		
		12	0.20		
		13	0.50		
		14	1.00		
	3		0.25		
Subtotal			3.60	5.0	10
Iao		16	0.25		
	7		2.30[c]		
	9		0.15		
	10		0.25		
Subtotal			1.85	11.0	50
Waikapu	11		1.00	3.0	10
TOTAL FOR WAILUKU AREA			16.8	47.5	--

1 Estimated by Stearns (1942, p. 212-213).
2 Estimated by Stearns (1942, p. 46).
3 Table 2.
a Flow exceeded 90 percent of the time (see fig. 7).
b Flow from clinker beds in lavas of the Honolua Volcanic Series.
c. Based on daily records of Maui County Dept. of Water Supply and Wailuku Sugar Co.

discharge about 5 mgd. Development-tunnel discharge of dike water is about 9.0 mgd; however, only about 1.5 mgd of this is estimated to be water salvaged from underflow. Most of the tunnel flow would have discharged naturally into the stream channels below the diversions had it not been intercepted by the tunnels (Stearns, 1942, p. 195-198), whose main function is to collect high-level water at points where it will be convenient to develop it, that is, above ditch intakes. The locations of major springs and tunnels are shown in figure 7 and pertinent data on existing tunnels is given in table 5.

Nearly all high-level discharge is diverted for irrigation of cane fields in the Wailuku area or on the isthmus. The discharge of tunnel 7, however, is diverted by the Maui County Dept. of Water Supply for public use. Tunnel 7 was started in 1938 by the County and completed in 1945 by the Wailuku Sugar Co. Flow from the tunnel reached a peak of more than 7.5 mgd in 1945 during construction, and slowly declined to its present flow of about 2.3 mgd over a period of more than a year. The tunnel captures about 1.2 mgd of water which previously discharged from tunnel 6 and spring 15 in Black Gorge, both now dry. Under an agreement with Wailuku Sugar Co., under whose land the upstream half of the tunnel is dug, the County is entitled to about 1 mgd of free water, and an additional 1.3 mgd, which it may buy at a price of $55.00 per million gallons (Koichi Hamada, written communication, Sept. 1968).

Data on wells, shafts, test holes, and selected springs in the Wailuku area are given in table 6 and their locations are shown in figure 7.

Large-scale development of basal water in the Wailuku area began in 1948 with the completion of Wailuku Sugar Co.'s shaft number 33. Water from three wells extending 310 feet below the pump chamber, which is 30 feet above sea level, is lifted about 375 feet up an inclined shaft to the portal.

Table 5. RECORDS OF HIGH-LEVEL AND PERCHED DEVELOPMENT TUNNELS*

Number	Owner	Valley	Date constructed	Altitude (ft above msl)	Estimated yield (mgd)	Length (ft)
1	Hawaiian Commercial & Sugar Co. and Wailuku Sugar Co.	Waihee	1909	1,625	4.6	2,200
2	"	"	1909	1,650	1.0	2,500
3[a]	Wailuku Sugar Co.	Waiehu	1902	300	0.2	500
4	"	Iao	1906	1,425	0.1	2,500
5	Hawaiian Commercial & Sugar Co.	Waikapu	1906	1,475	--	Caved
6	"	"	1926	1,305	Dry	1,413
7	Maui County Dept. of Water Supply & Wailuku Sugar Co.	Iao	1938, 1945	787	2.0, 2.3[b]	5,000
8	Wailuku Sugar Co.	"	1900	700	--	Caved
9[a]	"	"	1900	440	0.2	1,000
10[a]	Hawaiian Commercial & Sugar Co.	"	1900	240	0.2	2,000
11	"	Waikapu	1900, 1906	1,800	1.0	2,943
12	"	"	1905	1,770	<0.01	1,650

* From Stearns, 1942, p. 213.
a Yielding perched water from younger alluvium.
b 1940 and 1951, respectively.

Table 6. RECORDS OF DRILLED WELLS, TEST HOLES, SHAFTS, AND SPRINGS IN THE WAILUKU AREA

Name	USGS No.	Owner	Year constructed	Use*	Casing diameter (in)	Casing length (ft)	Depth (ft)	Altitude (ft above msl)	Water-level measurement		Chloride concentration		Yield*	Aquifer*	Records*	Remarks
									Date	Ft above msl	Date	Mg/l				
Waikapu	14	Div of Water & Land Dev.	1961	T,O	8	609	757	551	2/15/61 2/18/68	12.00 17.17	2/15/61	15	90 gpm	-	(1)	40-foot drawdown at 90 gpm. Continuous water levels 1967-68.
Mokuhau 1	15A	Maui County Dept of Water Supply	1953	PS	18	411	600	353	5/30/53 3/17/67	21 21.2			3 mgd	W	(2)	Semi-daily water levels 1961-67.
Mokuhau 2	15B	"	1953	PS	18	422	600	353	5/30/53 3/10/67	21 21.3	1/14/64	35	3 mgd	W		"
Ex-1	15C		1950	T,A	3/4	432	431	310	9/26/50 5/15/51	27.26 27.45	--	--	--	A		
Ex-2, Fld. 45	15D		1951	T,O	3/4	570	585	484	5/15/51 3/17/52 4/16/68	23.73 24.5 23.4	--	--	--	W	(2)	Monthly water levels, 1952-58. Continuous water levels 1968.
Ex-3	15E		1952	T,A	--	--	466	364	3/21/52	26.85	--	--	--	W		
Mokuhau 3	15F		1967	PS	18	--	--	--	--	--	11/15/67	31	3 mgd	W		
--	18	Joseph Delara	1947	I	8	22	31	--	--	--	10/47 10/27/48	528 45	--	-		Used for lawn irrigation.
Maalaea	272	Div of Water & Land Dev	1965	T,O	8	187	219	164	3/1/67	2.77	3/1/67	250	400 gpm	W		Continuous water levels 1967-68.
Iao	T-102	Wailuku Sugar Co	1940	T,O	3/4	471	475	454	12/8/47 5/21/68	27.18 26.90	9/15/66 7/16/65	18 37	--	W	(3) (3) (1)	Monthly water levels 1940-57. Monthly chlorides 1940-66. Continuous water levels 1967-68.
--	T-103		1933	T,A	1-1/2	--	177	80	1933	65	--	--	--	A		
--	T-104		1935	T,A	1-1/2	--	22	14	1935	2	--	--	--	D		
Puu Hele	T-110		1933	T,O,A	3/4	313	325	313	12/47	6.4	1/19/60	208	--	W	(3) (3)	Monthly water levels 1939-57. Monthly chlorides 1939-60.
Fld. 63	T-112	Wailuku Sugar Co	1945	T,O	1-1/2	--	477	455	12/47	29.4	12/18/46 8/17/54	11 41	--	W	(3) (3) (1)	Monthly water levels 1945-55. Monthly chlorides 1946-56. Continuous water levels 1948-53, 1967-68.
Mill	T-113	Wailuku Sugar Co	1945	T,O,A	1-1/2	--	705	180	12/47 11/2/56	18.2 11.9	4/19/55	125	--	A	(3) (3)	Monthly water levels 1946-55. Monthly chlorides 1946-56.
--	399	Ernest Mendes	1967	D	4	30	530	475	1967	25±	8/20/68	21	1,500 gpd	W		Driller reported water at 450-foot depth.
Waiehu Golf Course Well	451	Waiehu Municipal Golf Course	1967	I	8	40	76	10	7/6/67	2.7			200 gpm	D		
Wailuku Shaft	33	Wailuku Sugar Co	1947	I	--	--	--	30	12/11/47	27.35	12/11/47	15	15 mgd	W		See p. 29 for further description.

* Use: D, domestic; PS, Public supply, I, irrigation; T, test hole; O, observation; A, abandoned.
Yield: Given in gpm (gallons per minute), gpd (gallons per day), or Mgd (million gallons per day).
Aquifer: W, Wailuku basalt; D, dune sand deposits; A, alluvium.

Records: (1) Water Resources Research Center, University of Hawaii.
(2) Maui County Department of Water Supply, Kahului, Maui.
(3) U.S. Geological Survey, Honolulu, Hawaii.

From the portal, the water is pumped up to the Waihee ditch and is used to irrigate the Wailuku Sugar Co. cane fields on the alluvial slope between Wailuku and Maalaea. Pumpage on an annual basis from 1948 to 1967 averaged about 5 mgd, and on a daily basis ranged from zero to more than 12 mgd. Because the water is used for supplemental irrigation, the frequency and rate of pumping depend upon rainfall conditions (fig. 8). During wet periods, pumping may be stopped for months at a time, whereas in a low-rainfall season, such as 1953, more than 12 mgd was pumped nearly continuously for 3 months (fig. 9). The combined capacity of the shaft wells, 15 mgd at present, will be increased to 22 mgd by the installation of larger pumps in the near future.

Wells 15A, 15B, and 15F (fig. 7), drilled on the north bank of Iao Stream, supply domestic water to an area including Wailuku, Kahului, Paia, Kihei, and Maalaea. Wells 15A and 15B began production in 1955, and well 15F was drilled in 1967. These three wells, known as the Mokuhau battery, are pumped at an average rate of less than 5 mgd at present, but have a combined capacity of about 12 mgd. The pumpage of the Mokuhau wells and shaft 33 represents the visible discharge from the basal aquifer. Their monthly and annual pumpage from 1948 through 1967 is listed in table 7 and shown graphically in figure 8. Pumpage from the Mokuhau battery, unlike that from shaft 33, is fairly steady throughout the year.

Except for a small but unknown number of shallow, low-yielding wells used for lawn and garden irrigation, there is little development of the thin local basal lens along the coast. The water yielded from such wells is brackish, and the possibility of obtaining satisfactory domestic or agricultural irrigation water from this source is small.

Perched ground water flowing from springs at the base of the consolidated dune deposits between Waiehu and Iao Valleys was used in the past to irrigate taro patches along the coast.

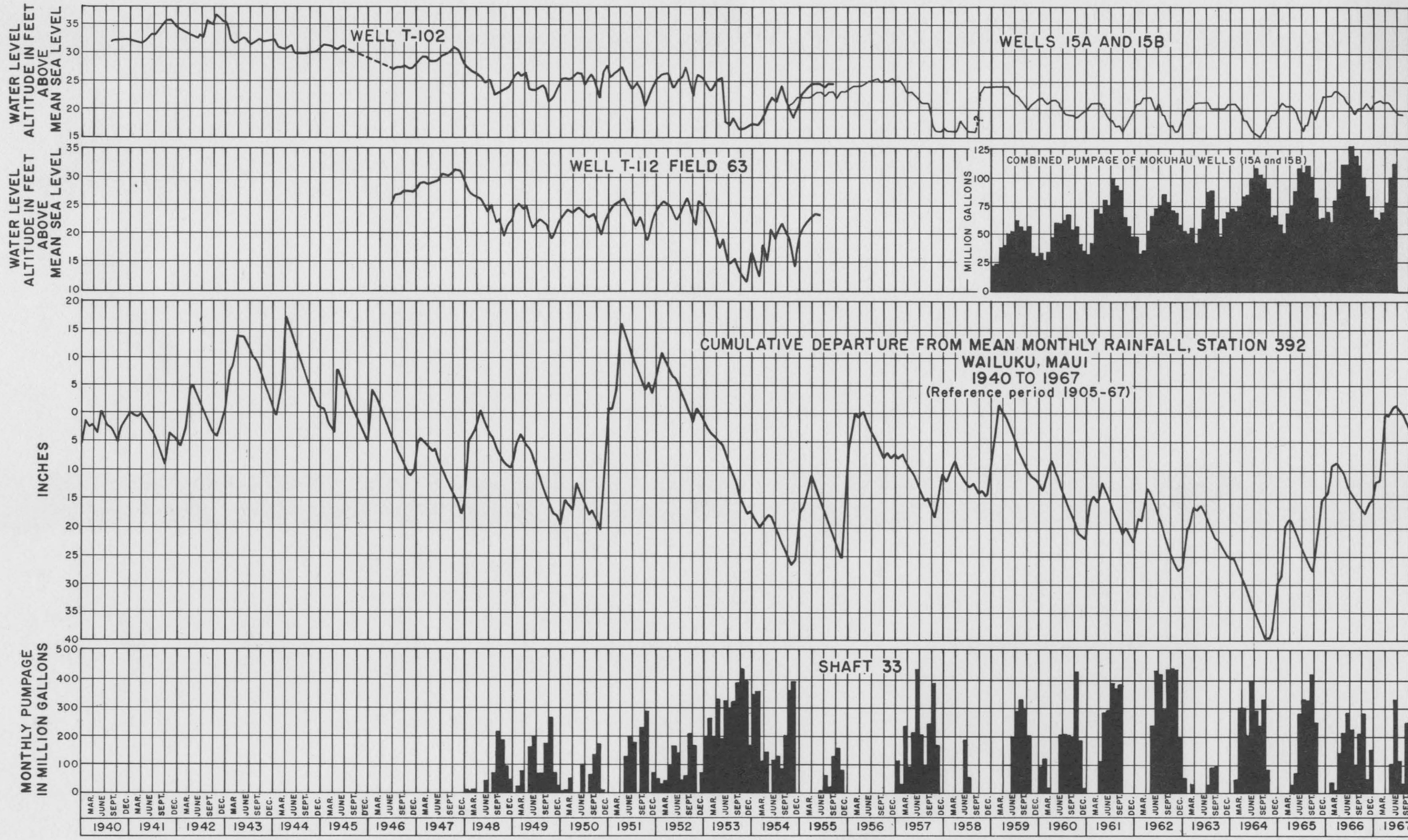

Figure 8. GRAPH SHOWING WATER LEVELS IN SELECTED WELLS IN RELATION TO PUMPAGE FROM SHAFT 33 AND CUMULATIVE DEPARTURE OF MONTHLY RAINFALL AT WAILUKU (392)

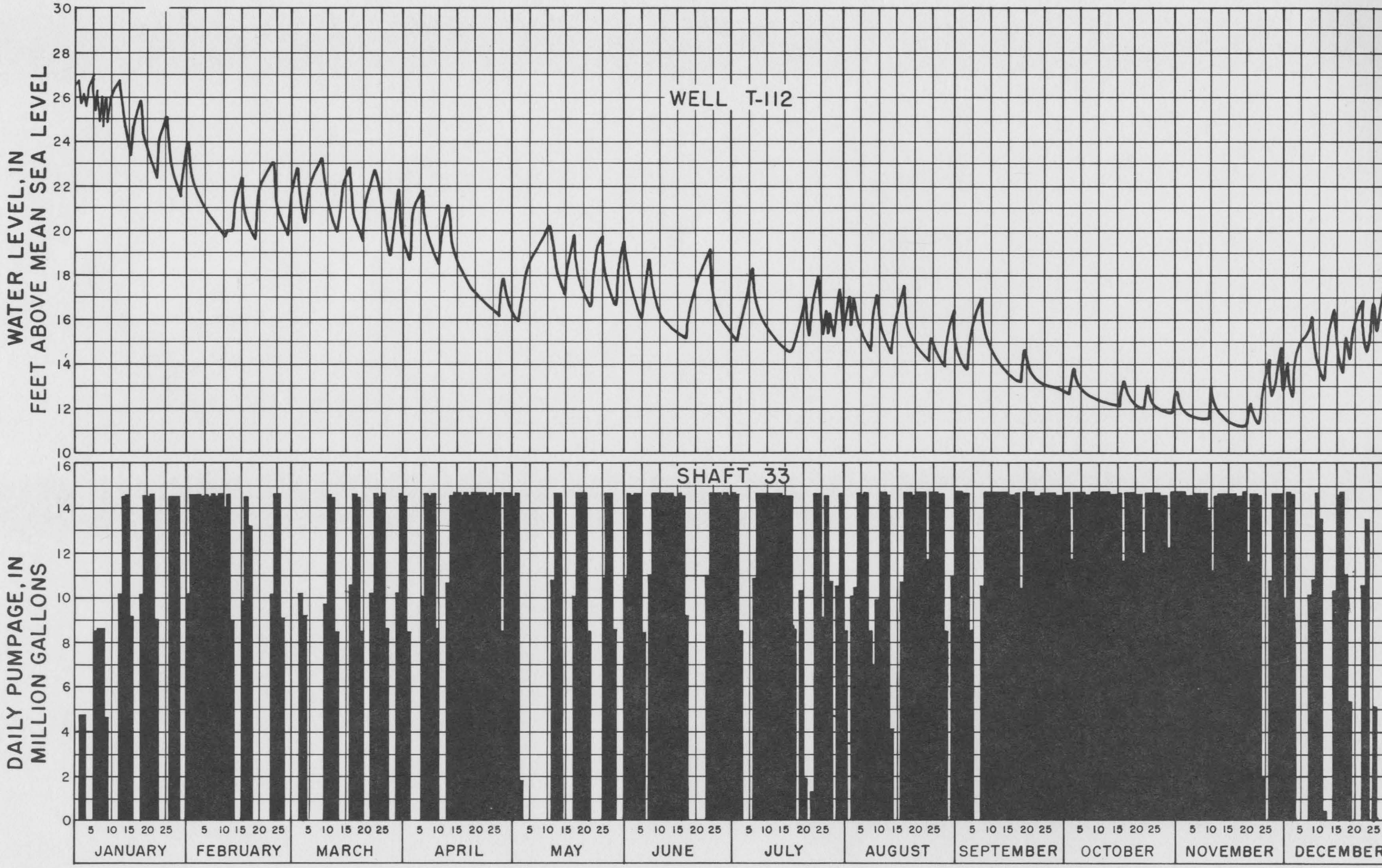

Figure 9. GRAPHS SHOWING WATER LEVEL AT WELL T-112 AND PUMPAGE AT SHAFT 33 during 1953

Table 7. MONTHLY AND ANNUAL PUMPAGE FROM THE MAIN BASAL LENS, 1948-67

Year	Well or shaft no.	Monthly pumpage (million gallons)												Annual pumpage (mg)
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	
1948	Shaft 33	--	--	--	--	--	--	--	--	--	--	--	--	732
1949	Shaft 33	--	--	--	--	--	--	--	--	--	--	--	--	725
1950	Shaft 33	14	16	56	4	6	105	53	67	138	177	9	0	645
1951	Shaft 33	0	4	0	25	128	199	181	151	237	293	58	76	1,352
1952	Shaft 33	56	34	45	106	168	139	46	62	212	171	0	74	1,113
1953	Shaft 33	213	265	201	337	194	327	304	326.	393	440	398	168	3,566
1954	Shaft 33	348	362	116	144	0	118	128	46	205	365	396	0	2,228
1955	Shaft 33	--	--	--	--	--	--	--	--	--	--	--	--	478
	Wells 15A, B	--	--	--	--	--	--	--	--	--	--	--	--	387
	Total	--	--	--	--	--	--	--	--	--	--	--	--	865
1956	Shaft 33	--	--	--	--	--	--	--	--	--	--	--	--	303
	Wells 15A, B	--	--	--	--	--	--	--	--	--	--	--	--	236
	Total	--	--	--	--	--	--	--	--	--	--	--	--	539
1957	Shaft 33	--	--	--	--	--	--	--	--	--	--	--	--	2,233
	Wells 15A, B	--	--	--	--	--	--	--	--	--	--	--	--	436
	Total	--	--	--	--	--	--	--	--	--	--	--	--	2,669
1958	Shaft 33	0	0	0	0	0	188	58	0	0	0	0	0	246
	Wells 15A, B	--	--	--	--	--	---	--	--	--	--	--	--	438
	Total	--	--	--	--	--	--	--	--	--	--	--	--	684
1959	Shaft 33	0	0	0	0	0	203	289	334	303	385	0	0	1,514
	Wells 15A, B	23	25	38	40	50	53	62	56	54	57	34	31	512
	Total	23	25	38	40	50	256	351	390	357	442	34	31	2,035
1960	Shaft 33	96	123	17	0	25	218	370	351	230	427	185	19	2,061
	Wells 15A, B	34	27	35	47	60	60	64	68	54	57	41	35	582
	Total	130	150	52	47	85	278	434	419	284	484	226	54	2,643
1961	Shaft 33	0	0	0	113	284	295	389	369	386	222	0	0	2,058
	Wells 15A, B	33	43	73	68	80	75	99	94	89	65	57	48	824
	Total	33	43	73	181	364	370	488	463	475	287	57	48	2,882
1962	Shaft 33	0	0	0	0	239	435	421	296	438	441	438	200	2,908
	Wells 15A, B	47	33	36	53	66	73	75	85	78	71	69	58	744
	Total	47	33	36	53	305	508	496	381	516	512	507	258	3,652
1963	Shaft 33	57	0	34	0	0	0	27	94	97	0	0	0	309
	Wells 15A, B	53	50	56	42	55	73	88	89	63	48	64	70	751
	Total	110	50	90	42	55	73	115	183	160	48	64	70	1,060
1964	Shaft 33	0	47	293	302	206	395	291	240	333	82	0	0	2,189
	Wells 15A, B	73	71	75	84	85	99	108	103	99	90	66	67	1,020
	Total	73	118	368	386	291	494	399	343	432	172	66	67	3,209
1965	Shaft 33	0	0	0	27	74	282	329	328	419	249	0	0	1,708
	Wells 15A, B	58	51	69	75	89	108	105	111	101	83	62	64	976
	Total	58	51	69	102	163	390	434	439	520	332	62	64	2,684
1966	Shaft 33	0	37	15	143	212	282	223	99	212	282	52	154	1,711
	Wells 15A, B	70	61	80	90	112	112	128	120	111	99	84	72	1,139
	Total	70	98	95	233	324	394	351	219	323	381	136	226	2,850
1967	Shaft 33	0	0	0	0	104	331	115	37	247	289	0	0	1,123
	Wells 15A, B	65	64	70	78	100	113	--	--	--	--	--	--	--
	Total	65	64	70	78	204	444	--	--	--	--	--	--	1,123

Stearns (1942, p. 131) estimated that developed flow from these springs amounted to 750,000 gpd. Taro is no longer grown in the coastal areas, and much of the water previously developed now flows to waste and to support phreatophytes growing in coastal marshes (fig. 7). However, water from well 451 is used for irrigation of the fairways and greens of Waiehu Municipal Golf Course. The total area of the golf-course grounds is about 50 acres, and the yield of well 451 is about 400,000 gpd. Ground water perched in younger alluvial gravels in Waiehu and Iao Stream channels is presumably still developed by tunnels 3, 9, and 10. These tunnels were not examined during this study, but Stearns (1942, p. 213) estimated their combined discharge at 600,000 gpd.

Effect of Development on the Main Body of Basal Water. Water-resources development in the Wailuku area, beginning with the diversion and application of high-level streamflow for cane irrigation in the late nineteenth century, and more recently by pumping, has probably affected the basal water in two opposing ways. Increased recharge by deep percolation of diverted irrigation water has added to ground-water storage in the basal-water body. The magnitude of increase in recharge and storage is impossible to determine because of the absence of ground-water data before and during the early stages of development. It may have been small, owing to the low permeability of the alluvium overlying the lens, but, at any rate, the natural equilibrium of the basal-water system was probably disturbed, and a new equilibrium established. Discharge by underflow probably increased slightly as a result of the increased recharge.

In an opposite effect, the more recent practice of pumping directly from the basal-water body has caused a reduction in storage and a slight decline in recorded water levels. The response of water level to the pumping of Wailuku shaft is shown in the hydrograph of well T-102 (fig. 8). From 1940 to 1948, before completion of the shaft, water levels in well T-102 ranged between 27 and 36 feet above mean sea level (all water levels are in feet above mean sea level hereafter), and averaged slightly over 30 feet. After pumping from the shaft began in 1948, the water level declined to about 23 feet, and then stabilized at an average altitude of about 25 feet between 1948 and 1953.

The effect of pumping is apparent in the monthly water-level fluctuations in wells 15A and 15B (fig. 8). Monthly water-level measurements in these wells correlate directly with pumpage. Water-level fluctuations, in response to rainfall variation, seem to occur on an annual or seasonal rather than a monthly basis.

Apparently the basal-water system has reached a new equilibrium, which accommodates the stress imposed by the Wailuku shaft and the Mokuhau battery pumping. Water-level records for the period 1948-53 show that water levels in well T-112 stabilized at various levels depending upon the pumping rate of the Wailuku shaft. During periods of heavy pumping, such as September through November 1953, water levels declined continuously until pumping stopped (fig. 9). If pumping were continued, a new equilibrium would have been reached under which water levels would stabilize as water salvaged from underflow equaled the increased pumpage.

Pumping has had little effect on the chloride concentration of the basal water. Recorded chloride concentrations range from about 15 to 40 mg/l (milligrams per liter) and the most recent samples are around 30 mg/l, which indicates that pumping may have caused a very slight increase. There is poor direct correlation between monthly pumpage and monthly chloride concentrations; however, the small range of recorded chloride concentration makes such comparison meaningless.

Future Development--Sources and Problems

Water is generally available in amounts adequate for present needs in the Wailuku area. However, demand for supplemental irrigation water exceeds the supply during occasional droughts, and continued population growth here and in neighboring areas will ensure that more domestic water will eventually be required.

The economic feasibility of further development of the high-level ground-water reservoir is difficult to judge at the present time. Stearns (1942, p. 196-198) estimated that most of the existing tunnels were not effective in salvaging underflow. To know whether or not it is worthwhile to lengthen or to bulkhead existing tunnels or to drive new ones requires that dikes be accurately mapped and existing tunnels and spring sites be reexamined. Streamflow measurements near diversion points are needed to determine developed base flow more precisely. In some valleys, it may be feasible to drill wells in order to tap high-level dike water as was done in Honokowai Valley in the Lahaina area (Yamanaga and Huxel, 1968).

The perched water, except in a few instances, is probably an uneconomical source for development of large quantities of additional water.

The ground water in the transitional area between Kahakuloa and the District boundary (fig. 7) could probably be successfully developed by wells with the resultant partial salvage of water now wasting to sea as underflow.

The reportedly high water level in well 399 (p. 27) needs to be checked by actual measurement or by surveying in the precise altitude of the well. In addition, the performance of the well should be tested thoroughly. If the basal water underlying the area between Waihee and Kahakuloa Valleys is impounded, it might prove to be a source of additional domestic water.

Safe Yield of the Basal-Water System. The basal water that underlies the area between Waikapu and Waihee Valleys is the most reasonable source of additional ground water from the area. The main problem is to determine the safe yield of the basal system. The safe yield is the rate at which water may be economically withdrawn for use without causing an unacceptable increase in chloride concentration. The safe yield of the system as a whole may be considerably greater than the combined safe pumping rate of individual well batteries, and depends upon distribution or spacing of wells, the permeability of the aquifer, and the frequency and intensity of pumping throughout the year. In addition, the overall safe yield of the system will be influenced by the degree of interconnection between various parts of the reservoir--for example, between the parts north and south of Iao Valley--and by the nature of the fresh water-salt water interface and the effectiveness with which the Ghyben-Herzberg principle operates in response to pumping drawdown.

Two of the major flow components of the basal-water system are recharge by underflow from the high-level reservoir, and discharge by underflow. A large part of the water discharged by underflow can be salvaged, for use by pumping withdrawals. It will be possible to estimate the safe yield of the system by observing cause and effect relations between pumping, on the one hand, and water levels and chloride concentration, on the other.

The combined pumping rate, on an annual basis, of the Mokuhau battery and the Wailuku shaft is about 8 to 10 mgd or 4 to 5 mgd each. This rate is apparently within the safe yield of the system, as chloride concentrations have remained low and long-term water levels relatively stable, up to the present time. Large, seasonal water-level declines, as in well T-112 during 1953 (fig. 9), which are not accompanied by an increase in chloride content, may indicate the possibility that the main basal-water body is connected remotely with salt water.

NEED FOR FURTHER INVESTIGATIONS

This report has presented a generalized picture of water resources in the Wailuku area. The information provided is not sufficient for long-term, detailed planning for the development and allocation of these resources, and further observations and investigations are needed to determine more definitely the amounts of developable fresh water available. The following outline lists the main categories of information needed, the kinds of work to be done, and the areas where the opportunity for water-resource development appears to be favorable.

1. Establishment of additional rain gages in the wet uplands where most of the rain falls.

2. Installation of stream-gaging stations on Waihee and Waikapu Streams to supplement records available on Kahakuloa and Iao Streams. Data from all these stations will permit a better estimation of total runoff from the area. Dry-weather or base flow can be obtained from plantation records of diversions from the streams.

3. Determination of the extent and hydrologic characteristics of the main basal- and dike-water systems in the area.

   a. Remap the location and orientation of the dikes in all major valleys.

   b. Examine the nature of the contact between the alluvium and the basalts of the Wailuku Volcanic Series.

   c. Determine the permeability variations in the basalts of the Wailuku Volcanic Series in major valleys.

   d. Determine the hydrologic properties of the older and younger alluvium.

e. Determine the relation of loss and gain properties of streams to the geologic properties of the rocks.

4. Estimation of the fresh water available on a sustained basis from the ground-water systems in the various parts of the area.

a. Make observations of water levels and salinity on a continuing basis at selected wells, springs, and shafts, and record pumpage from all wells.

b. Record and analyze the effects of pumping and other developmental stresses on the basal-water system in the area between Waikapu and Waihee Valleys.

c. Collect records of dry-weather or base flow at points of maximum flow in major stream valleys.

d. Drill test holes in Waikapu and Waihee Valleys to define the limits of the dike-water system, and in Kahakuloa Valley to determine the nature of the ground-water system.

The most important parts of the Wailuku area for water-resource development are as follows:

(1) The area between and including Waikapu and Waihee Valleys for the development of basal water underlying the alluvial slope and dike water in the valleys above the alluvium.

(2) The area between and including Kahakuloa Valley and the Western District boundary for salvage of underflow discharging to sea.

(3) The area between Waihee and Kahakuloa Valleys for the development of basal-water supplies.

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